

# Time Production and EEG Alpha Revisited

Joseph Glicksohn<sup>\*†</sup>, Aviva Berkovich Ohana<sup>†</sup>  
Tal Balaban Dotan<sup>†</sup>, Abraham Goldstein<sup>†</sup>, Opher Donchin<sup>‡</sup>

## Abstract

If one accepts the notion of an internal clock, then one must further presume that *time production* is attuned with the rate of functioning of the clock's pacemaker. We look at the individual's online EEG recording while performing a time-production task, placing one focus of interest on the individual's *peak alpha frequency* (PAF), and a second on alpha power and its topography. The participants completed a time-production task with online EEG recording, twice during a single session in the lab, in a pre-post design. We present data concerned with the topography of post-pre differences in alpha power, both during time production and during rest, as a function of an intervening period of either restful wakefulness or motor activity. Our major finding is that left PAF and right PAF mutually suppress each other in predicting produced duration, and that given the size and sign of their regression weights, it is a left-right asymmetry in PAF that plays a pivotal role here. On computing a left-right asymmetry index for PAF, we found that this index had a significant correlation with the mean log-transformed produced duration ( $r = .364, p < .01$ ), and that the relationship is stronger among females ( $r = .500, p < .005$ ).

**Key Words:** time production, psychophysics, EEG alpha, EEG theta, peak alpha frequency, individual differences

NeuroQuantology 2009; 1: 138-151

## 1. Introduction

The notion of an internal clock underlying time perception (Burle & Casini, 2001; Treisman & Brogan, 1992; Wearden, 1991) is one that comes under attack every decade, with somewhat clockwork precision. Treisman's (1963) model served as the impetus for a number of studies forty years ago (Carlson & Feinberg, 1968, 1970) –which are now conveniently forgotten– subsequently dismissed by various authors who posited, what

Ivry and Hazeltine (1992) termed, a *timing-without-a-timer* approach, thirty years ago. Proponents of an internal clock remained undaunted, and have simply forged on over the past twenty years under the guise of scalar expectancy theory (Wearden & Culpin, 1998; Wearden, Philpott, & Win, 1999). And just when a *rapprochement* had finally been achieved in the literature ten years ago, wedding the internal clock with both attention and memory in the attentional gate model (Zakay & Block, 1997; Zakay, Block, & Tsal, 1999), internal-clock *afficionados* are now again under siege (Lewis, 2002; Lewis & Miall, 2006; Marchetti, 2008).

This special issue concerned with time and the brain provides us with a platform to present some of our current work addressing

Corresponding author: Joseph Glicksohn, Ph.D.

Address: \*Department of Criminology, Bar-Ilan University, Ramat Gan, 52100, Israel, †The Leslie and Susan Gonda (Goldschmied) Multidisciplinary Brain Research Center, Bar-Ilan University, ‡Department of Biomedical Engineering, Ben-Gurion University of the Negev

Phone: +972-3-5318221

e-mail: jglick@bgu.ac.il

ISSN 1303 5150

the notion of an internal clock. Our data will certainly not convince the reader one way or the other (Wearden, Denovan, Fakhri, & Haworth, 1997) –we ourselves are having a hard time here fathoming the depths to which individual differences can somewhat neutralize what should have been simple *pre-post* differences in cortical arousal, that key factor influencing the internal clock of which we speak (Cahoon, 1969; Treisman, 1984; Wearden *et al.*, 1999). Nevertheless, the data are interesting, and the approach is perhaps naïve, but certainly straightforward: The experimental design is a simple pre-post single session; the time-production task employed is not dependent on any particular theory, and in fact can be analyzed in two complementary ways; the EEG recording is both comprehensive, in that a large number of leads are employed, and focused, in that we look at particular sites within both hemispheres; and the data-analytic approaches which were adopted are all easily replicable. Let us therefore present the rationale underlying our work.

If one accepts the notion of an internal clock (Allan, 1998; Block, 1990; Macar, 1985, 1993; Macar & Vidal, in press), then one must further presume that *time production* is attuned with the rate of functioning of the clock's pacemaker (Baudouin, Vanneste, Isingrini, & Pouthas, 2006; Ozel, Larue, & Dosseville, 2004; Pouthas & Perbal, 2004). That is to say, a faster rate of functioning will lead to shorter time productions, while a slower rate of functioning will lead to longer time productions (Bindra & Waksberg, 1956; Binkofski & Block, 1996; Glicksohn, 2001). Of course, without an independent assessment of this rate of functioning, the line of thought presented above is clearly circular. There is, however, a way of breaking this impasse—that is, to look at the individual's online EEG recording while performing the task (Adam, Rosner, Hosick, & Clark, 1971; Coffin & Ganz, 1977; Gibbons & Rammsayer, 2004; Legg, 1968; Makhin & Pavlenko, 2003; N'Diaye, Ragot, Garnero, & Pouthas, 2004), and this is the approach we follow here.

The hypothesized correlation between the rate of functioning of the pacemaker and the alpha rhythm of the EEG has a venerable past, extending back to Norbert Weiner's 'brain

clock' hypothesis developed in the 1950's (Barlow, 1993, p. 279). More recent conceptions include an array of oscillatory processes (Ivry & Hazeltine, 1992, p. 186). Block's (1990, p. 4) conclusion regarding the failure of attempts to show the hypothesized link between internal-clock models and the alpha rhythm (e.g., Treisman, 1984) probably needs to be amended given Treisman's subsequent work (Treisman & Brogan, 1992; Treisman, Cook, Naish, & MacCrone, 1994; Treisman, Faulkner, Naish, & Brogan, 1990). Our reading of this literature suggests that we place one focus of interest on the individual's *peak alpha frequency* (PAF), which was shown twenty-five years ago to be an important EEG alpha index (Osaka, 1984). PAF is receiving renewed research attention (Angelakis, Lubar, & Stathopoulou, 2004; Angelakis, Lubar, Stathopoulou, & Kounios, 2004; Clark *et al.*, 2004), differentiating individuals in terms of memory performance. While PAF is a relatively stable intraindividual index (Neuper, Grabner, Fink, & Neubauer, 2005; Oken & Chiappa, 1988; Salinsky, Oken, & Morehead, 1991), it exhibits large interindividual differences (Klimesch, Sauseng, & Gerloff, 2003; Osaka, Osaka, Koyama, Okusa, & Kakigi, 1999). PAF increases with task demands (Osaka, 1984), and is correlated with RT (Jin, O'Halloran, Plon, Sandman, & Potkin, 2006). It is thus a short distance to go in making the suggestion that PAF should be indicative of the rate of functioning of the pacemaker, hence should be correlated with the data of time production.

PAF is one alpha parameter looked at in the studies reported here. A second is that of alpha power and its topography. Previous studies have indicated a relationship between time production and left-central alpha activity (Makhin & Pavlenko, 2003), and an extremely long time production in a patient having a left-frontal lesion (Binkofski & Block, 1996). Other studies have implicated different cortical areas, including the right dorsolateral prefrontal cortex (Rubia & Smith, 2004; Smith, Taylor, Lidzba, & Rubia, 2003), the right-parietal cortex (Mohl & Pfurtscheller, 1991), the right-parietal cortex coupled with both left- and right-prefrontal cortex (Basso, Nichelli, Wharton, Peterson, & Grafman, 2003), and prefrontal cortex (Rubia, 2006; Tracy, Faro, Mohamed,

Pinsk, & Pinus, 2000). Of course, such issues as whether a motor response is involved, the modality of the presented target, the use or not of chronometric counting, the load on working memory, and so forth will all inevitably play a role in determining which of these cortical areas are involved in any study concerned with time perception. However, a broad, bilateral anterior-posterior network is indicated (Lewis & Miall, 2006).

Our indices of time production enable both internal checks on individual consistency and alignment with two prominent models of the process of time production. The first model assumes that produced duration ( $T$ ) is related to target duration ( $D$ ) according to the psychophysical power function (Brown & Stubbs, 1988; 1992; Glicksohn, 1996), hence when both produced and target durations are log-transformed, rendering a linear function, the simple intraindividual regression equation [i.e.,  $\log(T) = \alpha + \beta \log(D)$ ] provides four measures of relevance. These are the slope of the line ( $\beta$ ), which is equivalent to the exponent of the power function, which is either veridical ( $= 1$ ; Allan, 1979) or converges on the value of 0.9 (Eisler, 1976; Grondin, 2001); the intercept ( $\alpha$ ), which is equivalent to the log-transformed measure constant of the power function, and which is very likely to reveal individual differences in both state and trait (Borg & Marks, 1983; Glicksohn, 1996; Ivry & Hazeltine, 1995); the coefficient of determination ( $r^2$ ) for the regression, which indicates to what degree can a linear fit to the data be supported; and the mean log-transformed produced duration [mean  $\log(T)$ ], which coincides with the log-transformed geometric mean, which some authors have considered to be preferable for data analysis (Rule, 1993). While the data could be analyzed at the group level, it is patently clear that individual differences abound (Allan, 1983; Fraisse, 1984; Zakay, 1990), hence the computation of individual regression equations, and the careful pruning of outliers, is mandatory, as we shall show in the Results section.

The second model assumes either an implicit or explicit form of chronometric counting, suggesting that a multiplicative function of two key components (the number of subjective time units and their size) should

predict time production (Glicksohn, 2001). In the Results section of this paper, we show how we derive an estimate of the size of the subjective time unit employed by the participant, and also how this is related to the mean log-transformed produced duration. The issue of whether chronometric counting should be discouraged (Kladopoulos, Hemmes, & Brown, 2004; McDonald, Schleifer, Richards, & de Wit, 2003; Mimura, Kinsbourne, & O'Connor, 2000; Noulhiane, Mella, Samson, Ragot, & Pouthas, 2007; Rule & Curtis, 1985) or encouraged (Coelho *et al.*, 2004; Miró, Cano, Espinosa-Fernández, & Buela-Casal, 2003; Myers & Tilley, 2003) becomes a moot point, given the fact that explicit counting will inevitably improve performance (Grondin, Meilleur-Wells, & Lachance, 1999; Hinton, Harrington, Binder, Durgerian, & Rao, 2004; Ryan, Henry, Robey, & Edwards, 2004), either reducing intraindividual variance for the various produced durations (Wearden, 1991), or making this variance independent of target duration (Grondin, Ouellet, & Roussel, 2004)—hence violating the scalar property assumed by scalar expectancy theory (Hinton & Rao, 2004), while still supporting the notion of a *pacemaker-counter* internal clock (Glicksohn, 2001; Killeen, 1992). Furthermore, if chronometric counting is involved, then the anterior-posterior network will be revealing here (Lalonde & Hannequin, 1999).

Generally speaking, one would expect that moderate motor activity within the session would increase cortical arousal (Anderson, 1990), hence should increase the rate of functioning of the pacemaker. In contrast, restful wakefulness should either have no marked effect on cortical arousal or should decrease cortical arousal (Jacobs & Friedman, 2004), hence should decrease the rate of functioning of the pacemaker. With such a pre-post design, we can assess within individuals whether such expected changes in arousal level are found, looking at both alpha and theta activity in baseline EEG, and whether such expected changes in pacemaker rate are found, looking at both the time-production data and the online EEG during time production. Given two assessments of both baseline and task, we are in a better position for understanding relative change (Fahrenberg, 1988).

## 2. Method

### 2.1 Design

The participants completed a time-production task with online EEG recording (Glicksohn, 2003), twice during a single session in the lab, in a pre-post design. These participants were drawn from two studies currently in progress in our lab, one concerned with meditation and the EEG (for a review of this literature, see Cahn & Polich, 2006), the other concerned with motor training and the EEG (for a review of this literature, see Hillman, Erickson, & Kramer, 2008). Our present report refers to the control conditions for these latter studies.

For the first study ( $n = 27$ ; 15 males and 12 females), this is the pre-post control condition of restful wakefulness, wherein participants are asked to “relax as best as you can without falling asleep”, the so-called baseline, resting state of the brain (Kounios *et al.*, 2008; Mantini, Perrucci, Del Gratta, Romani, & Corbetta, 2007; Mazoyer *et al.*, 2001). These participants are matched in age and gender to the participants practicing meditation, whose data are not reported here. For the second study ( $n = 24$ ; 6 males and 18 females), this is the pre-post preliminary session of motor training, wherein participants are randomly allocated to two different forms of motor training (again, this difference is not of present interest), and continue practicing for a month. Motor training was based on the Quadrato Exercise, designed by the Patrizio Paoletti Foundation. The exercise consists of precise steps made in response to specific instructions. For present purposes, data from the first session irrespective of particular form of motor activity will be reported.

### 2.2 Participants

The participants of this study are mainly drawn from an undergraduate pool of students and their friends, ranging in age between 19 and 46. Given the fact that there is no random allocation of participants to these two control conditions, we shall report their pre-post data separately. On the other hand, given the fact that they were drawn from a common pool, we shall pool participants when reporting on their pre data for both baseline EEG and EEG during the first task of time production. Of a total of 59 volunteers participating in these control conditions, 51 (21

males, and 30 females) provided us with a complete data set, which we subsequently report. Individuals not further considered include 4 having a noisy EEG recording, and 4 exhibiting aberrant performance on the time-production task.

### 2.3 Time Production

Four short durations of 4, 8, 16 and 32 seconds served for the time-production task. The participant was required to remain with eyes closed while producing each of these target durations by pressing a finger button (Glicksohn, 1996) for the required period of time. Each target interval was produced twice, the target durations being presented in random order to the participant. The participants were subsequently requested to report on the strategy they adopted in performing the task. Produced and target durations (in sec) were log-transformed (to base 2), with required durations rendering thereby a linear scale ranging between 2 and 5, with a midpoint value of 3.5; produced duration was then regressed on required duration.

### 2.4 Electrophysiological Measurement

EEG was recorded using a 65-channel geodesic net (Electrical Geodesics Inc.) at a 500 Hz sampling rate, referenced to the vertex (Cz), with analog 0.1-200 Hz band-pass filtering. The data were subsequently referenced offline to average reference, which is the most appropriate reference for the measurements of intra- and inter-anterior and posterior cortical activity (Hagemann, 2004). Impedance was kept under 40 k $\Omega$ , which is within the accepted range for this system (Arzouan, Goldstein & Faust, 2007; Ferree, Luu, Russell, & Tucker, 2001; Grieve, Emerson, Fifer, Isler, & Stark, 2003; Nunez *et al.*, 1997). EEG signals showing eye movements or muscular artifacts were manually excluded from the study. For present purposes, we focus on the bilateral anterior-posterior network defined by the following homologous leads: AF3, AF4, F3, F4, C3, C4, P3, P4, O1, and O2.

For each electrode of interest, 16 non-overlapping, artifact-free epochs of 2.048 sec duration were extracted for further analysis, for each condition of the study: baseline, and during time production prior to either restful wakefulness or motor activity, and baseline and

during time production subsequently. For each epoch, the power spectral distribution was computed and grouped into the various frequency bands. In the present report, we focus on power within the theta (4-8 Hz) and alpha (8-13 Hz) bands. Mean power (in  $\mu V^2$ ) was computed across epochs, and was then log-transformed. In addition, peak alpha frequency was extracted, at P3 and P4.

### 3. Results

#### 3.1 Time Production

For a minority of participants ( $n=9$ ), some aberrant values were noted in their data, and these data points were dropped prior to running the individual regressions. Inspection of the individual psychophysical functions subsequently confirmed the linearity assumption for all 51 participants,  $r^2$  values ranging between 0.937 and 0.999 at test, and 0.914 and 0.999 at retest. Mean log-transformed produced duration ranged between 2.51 and 4.41 ( $M = 3.63$ ) at test, and 2.46 and 4.36 ( $M = 3.63$ ) at retest. Turning to the slope value, ranging between 0.74 and 1.09 ( $M = 0.94$ ) at test, and ranging between 0.68 and 1.30 ( $M = 0.98$ ) at retest, and the intercept value, ranging between  $-1.11$  and  $1.71$  ( $M = 0.33$ ) at test, and ranging between  $-1.30$  and  $1.25$  ( $M = 0.23$ ) at retest, we find them to be negatively correlated, at both test ( $r = -0.50, p < .0001$ ) and retest ( $r = -0.43, p < .005$ ) as one would expect (Rule, 1993).

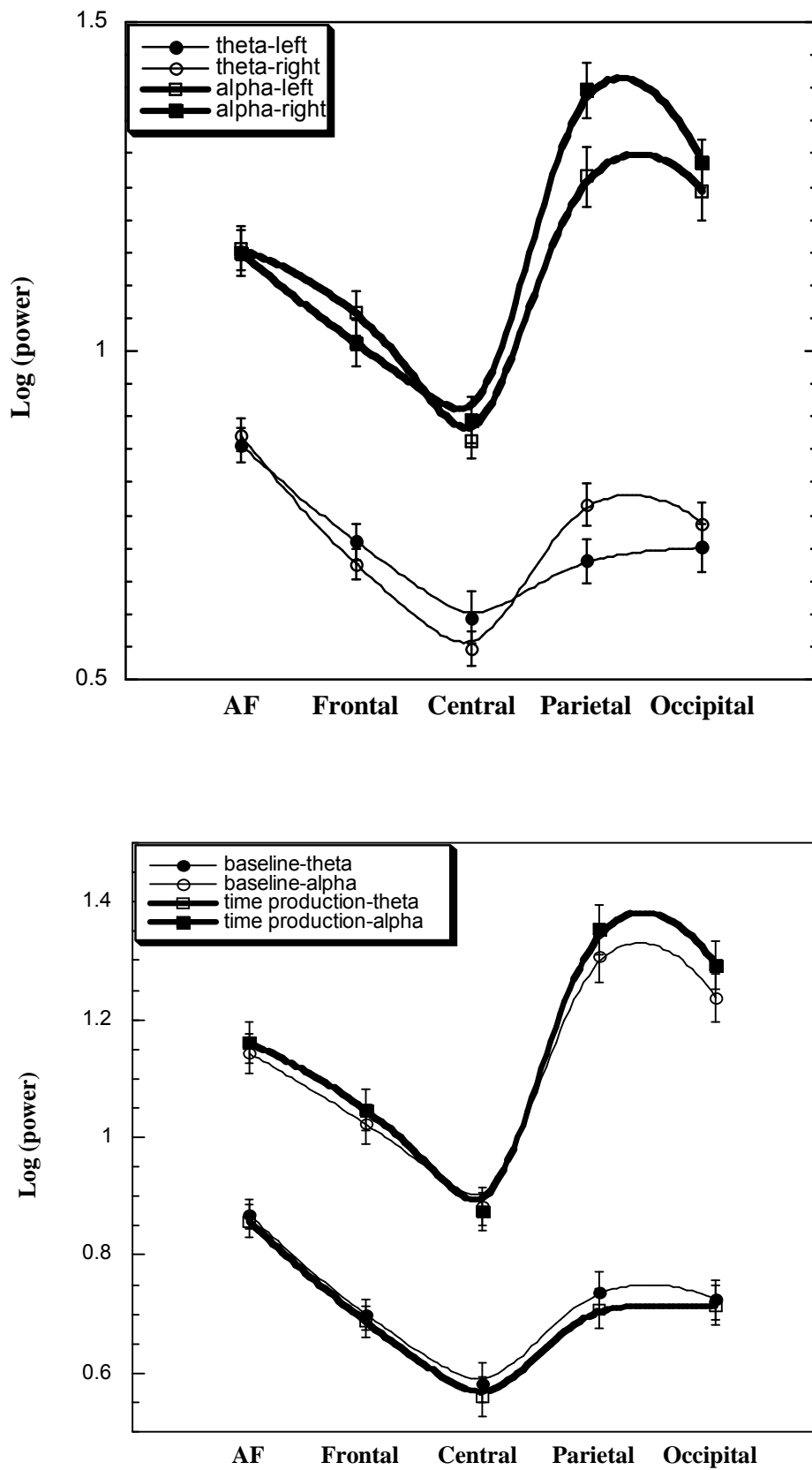
If the participant employs chronometric counting, and assuming that this rate of counting is consistent within task, then using the same log-transformed data, we can translate between the mean log-transformed produced duration and this rate of counting. Thus, if the multiplicative model (Glicksohn, 2001) holds, namely produced time ( $T$ )= $n$  (number of subjective time units) $\times S$  (size of subjective time unit), then after a logarithmic transformation (to base 2), mean log ( $T$ ) = 3.5 + mean log ( $S$ ). From this we can easily derive the size of the subjective time unit for that individual in that task. For the present data,  $S$  ranges between 0.50 and 1.89 ( $M = 1.15$ ) at test, and between 0.49 and 1.81 ( $M = 1.16$ ) at retest. All our participants reported employing chronometric counting, of one form or the

other (e.g., breath counting, counting "21", "22", etc.).

#### 3.2 EEG alpha and theta

Pooling the data for all participants at baseline, we look at eyes-closed resting wakefulness, compared with time production with eyes closed, prior to either remaining relaxed or being engaged in motor activity. We ran a Gender (male, female)  $\times$  Task (baseline, or time production)  $\times$  Band (theta, alpha)  $\times$  Hemisphere (left, right)  $\times$  Site (AF, F, C, P, O) analysis of variance (ANOVA) with repeated measures on the last 4 factors, adopting the Greenhouse-Geisser  $p$ -value for each and every effect, both in this analysis and as reported subsequently. The Band  $\times$  Hemisphere  $\times$  Site interaction [ $F(4, 196) = 4.96, MSE = 0.011, p < .01$ ] was found to be significant, as was the Task  $\times$  Band  $\times$  Site interaction [ $F(4, 196) = 4.88, MSE = 0.003, p < .005$ ], as well as various main effects and two-way interactions. Turning to the first interaction, and with respect to Figure 1, we see as one would expect, that power is much higher within the alpha band than within the theta band; and that alpha is dominant in both the right-parietal cortex and the left-frontal cortex. Turning to the second, we see higher alpha power and somewhat lower theta power during time production, relative to baseline.

We subsequently ran a Gender  $\times$  Condition (pre, post)  $\times$  Task  $\times$  Band  $\times$  Hemisphere  $\times$  Site ANOVA with repeated measures on the last 5 factors, separately for each study. For motor activity ( $n = 24$ ), the Condition  $\times$  Task  $\times$  Hemisphere interaction [ $F(1, 22) = 4.95, MSE = 0.006, p < .05$ ] was found to be significant, as was that of Gender  $\times$  Task [ $F(1, 22) = 6.68, MSE = 0.441, p < .05$ ] and various other two-way and three-way interactions. For relaxed wakefulness ( $n = 27$ ), the Gender  $\times$  Condition  $\times$  Task  $\times$  Band  $\times$  Hemisphere  $\times$  Site interaction [ $F(4, 100) = 3.51, MSE = 0.011, p < .05$ ] was significant, as was the Gender  $\times$  Condition  $\times$  Task  $\times$  Hemisphere  $\times$  Site interaction [ $F(4, 100) = 4.83, MSE = 0.002, p < .005$ ], and various three-way and two-way interactions.



**Figure 1.** Profiles (mean  $\pm$  standard error) of log-transformed theta and alpha power (in  $\mu V^2$ ) within each hemisphere; during baseline and during the task of time production

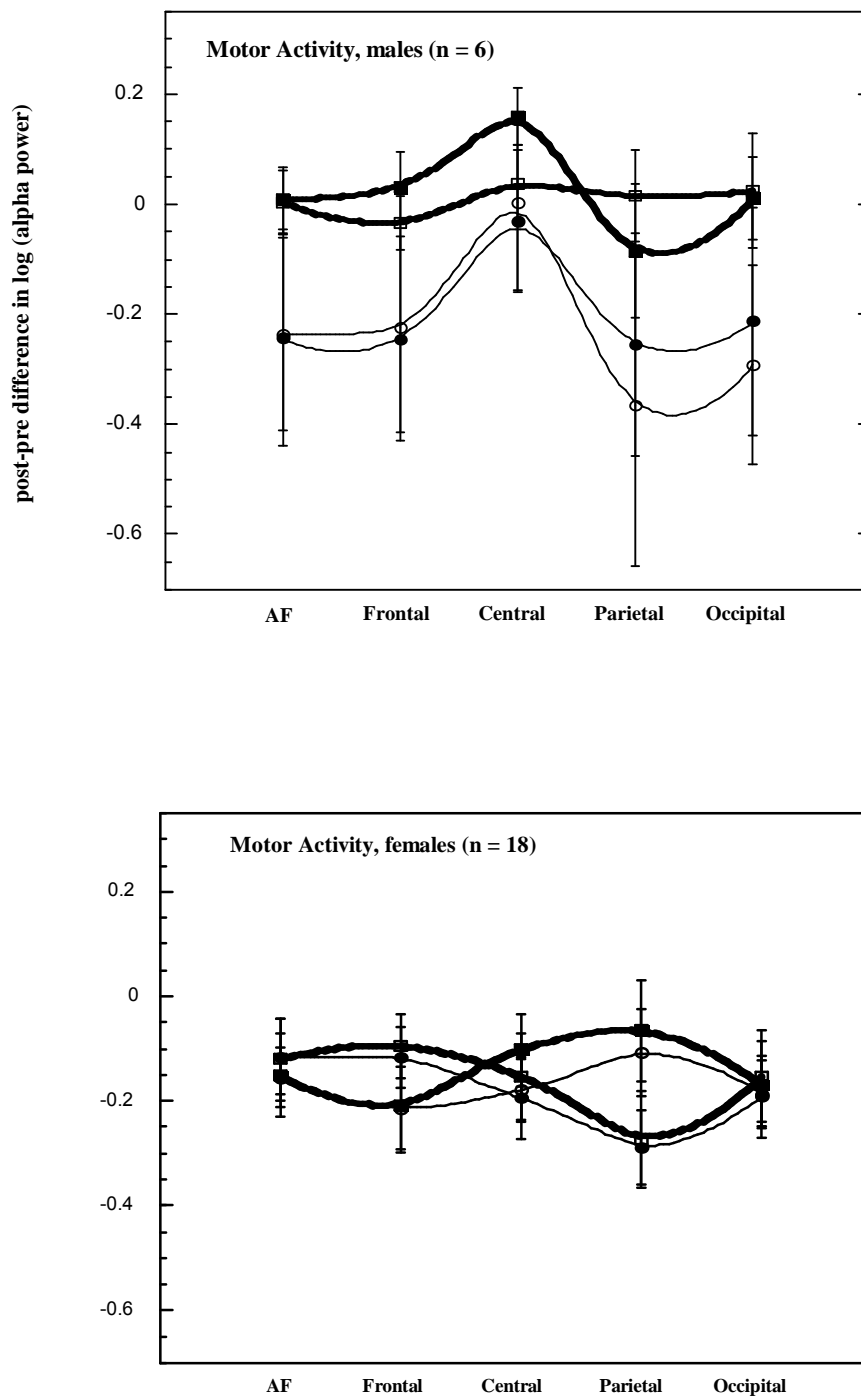
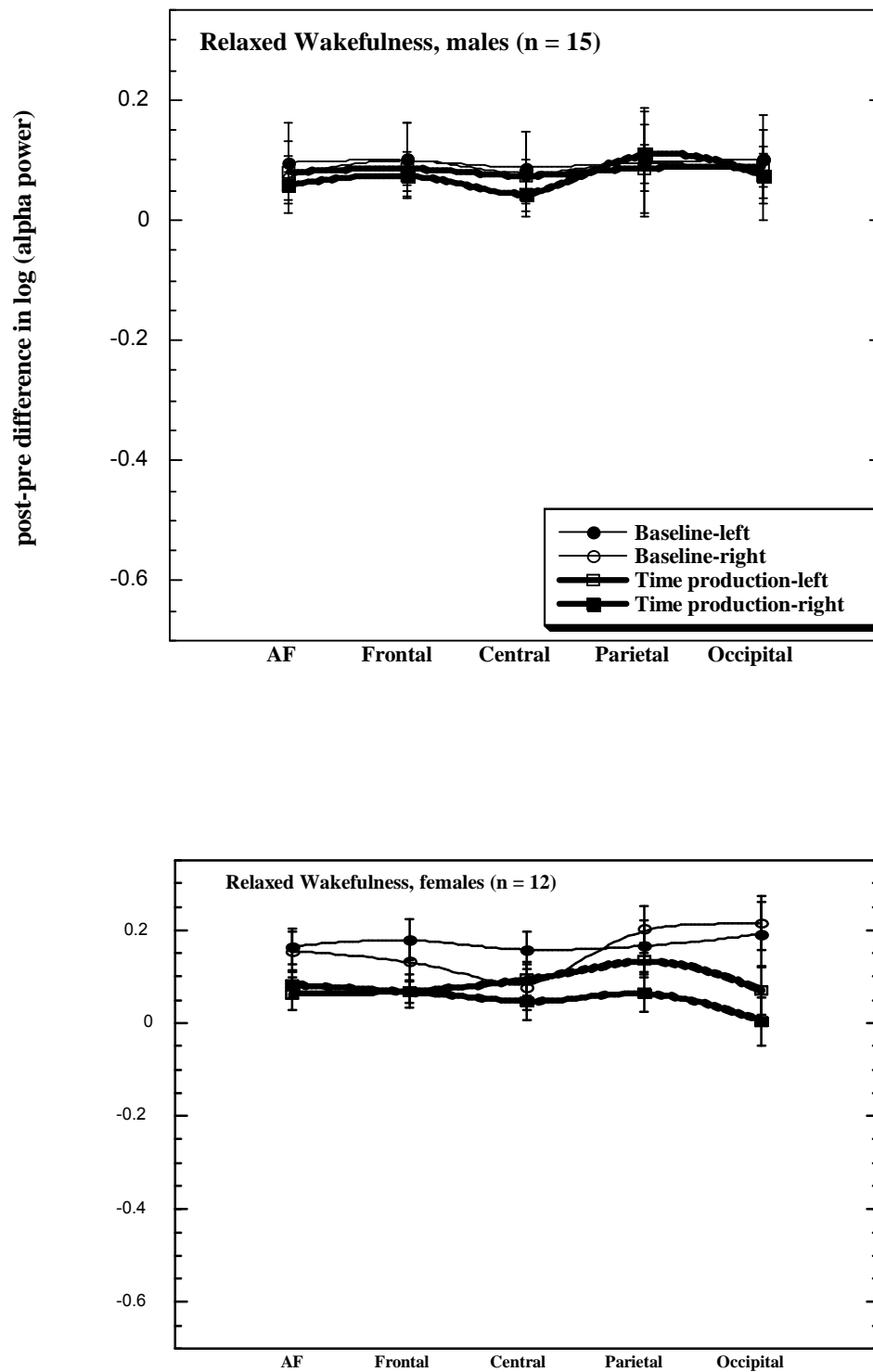
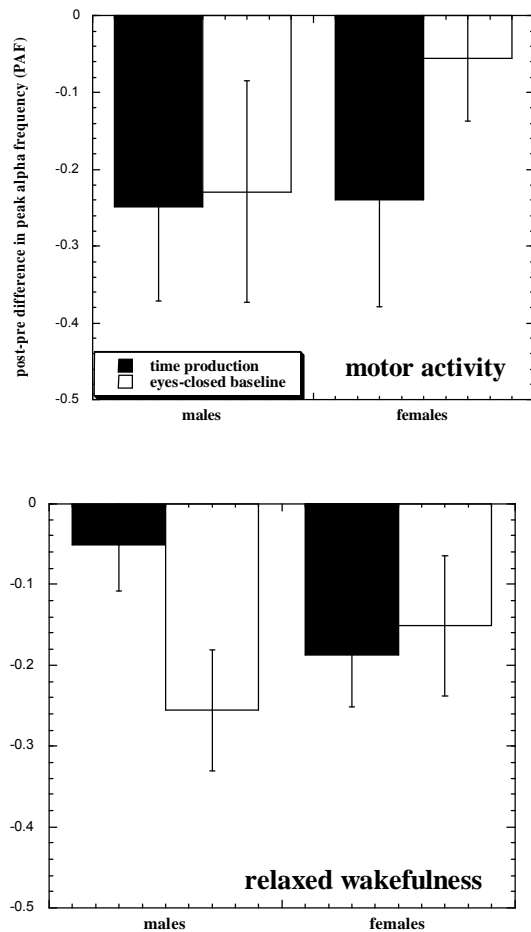


Figure 2. Please see next page



**Figure 2.** Profiles (mean  $\pm$  standard error) of post-pre differences in log-transformed alpha power (in  $\mu V^2$ ) for males and females, following motor activity or relaxed wakefulness



**Figure 3.** Profiles (mean  $\pm$  standard error) of post-pre differences in peak alpha frequency (in Hz) for males and females, following motor activity or relaxed wakefulness.

To reduce the data, we computed the post-pre difference score for both log (alpha power) and log (theta power) for each of these two studies, given that for motor activity there is a subsequent general reduction in alpha power, while there is an increase in alpha power following relaxed wakefulness. We focus on the alpha band in Figure 2. Apart from the data for the 6 males participating in the motor-activity condition, given the relatively larger samples in the other conditions, the data are much less noisy. Clearly, there is a global decrease in alpha power after motor activity for the females, irrespective of task, with an interesting anterior-posterior hemispheric torque. After relaxed wakefulness, there is a global increase in power, the data for the females showing more systematic variation, and more differentiation of task from baseline.

### 3.3 Peak alpha frequency

We ran a Gender  $\times$  Task  $\times$  Hemisphere ANOVA with repeated measures on the peak alpha frequency (PAF). Only the main effect for Task was significant [ $F(1, 49) = 6.64$ ,  $MSE = 0.134$ ,  $p < .05$ ], indicating an increase in PAF during time production ( $M = 10.38$ ), relative to baseline ( $M = 10.24$ ), as one would expect (Osaka, 1984). We subsequently ran a Gender  $\times$  Condition  $\times$  Task  $\times$  Hemisphere ANOVA with repeated measures separately for each study. For motor activity, the main effects for Task [ $F(1, 22) = 4.62$ ,  $MSE = 0.147$ ,  $p < .05$ ], Condition [ $F(1, 22) = 5.16$ ,  $MSE = 0.261$ ,  $p < .05$ ], and Gender [ $F(1, 22) = 5.12$ ,  $MSE = 5.170$ ,  $p < .05$ ] were all significant. For relaxed wakefulness, the main effects for Task [ $F(1, 25) = 4.35$ ,  $MSE = 0.152$ ,  $p < .05$ ] and for Condition [ $F(1, 25) = 19.40$ ,  $MSE = 0.072$ ,  $p < .001$ ] were significant, but not that of Gender [ $F(1, 25) < 1$ , *ns*]. Figure 3 presents the post-pre difference score in PAF for each of these two studies. Note the sharp decrease in PAF following motor activity, for time production but not for baseline among the females. In contrast, note the slight decrease in PAF following relaxed wakefulness, for time production but not for baseline, among the males.

### 3.4 Peak alpha frequency and Time Production

Finally, and most importantly, what is the relationship between PAF and time production? Pooling the data for all participants at test, and looking at the correlations between PAF in each hemisphere during time production and the mean log-transformed produced duration, we found nonsignificant correlations ( $r = .147$  for left PAF, and  $.020$  for right PAF, both *ns*). At first blush, this is devastating for the present thesis. We are, however, able to report on a *major* finding here. Employing *both* left PAF and right PAF in a multiple-regression analysis, we find their *joint* contribution to be substantial [ $F(2, 48) = 3.80$ ,  $MSE = 0.220$ ,  $p < .05$ ;  $R^2 = .137$ ], with intercept ( $b = 3.23$ ,  $p < .0005$ ), left PAF ( $b = 0.604$ ,  $p < .01$ ) and right PAF ( $b = -0.565$ ,  $p < .05$ ) all being significant. This is a classic example of a suppression situation in research (Tzelgov & Henik, 1991), where neither left nor right PAF has predictive faculty in separate, but are jointly related to performance. On uncovering this relationship, we ran similar analyses on the

other relevant variables, to rule out a number of alternative hypotheses. Based on this extensive data analysis, we note the following: (1) it is PAF during time production, and not at baseline, which is predictive; (2) it is PAF during time production at test, and not at retest, which is predictive; (3) the prediction is for either the mean log-transformed produced duration or the size of the subjective time unit, and not for either slope or intercept; (4) there is an even stronger relationship when the sample is restricted to the females ( $n = 30$ ;  $b = 3.31$ ,  $0.971$ ,  $-0.943$ , respectively, all at  $p < .01$ ;  $R^2 = .252$ ,  $p < .05$ ). We conclude that left PAF and right PAF mutually suppress each other in predicting produced duration, and that given the size and sign of their regression weights, it is a left-right asymmetry in PAF that plays a pivotal role here. Indeed, on computing a left-right asymmetry index for PAF, we found that this index had a significant correlation with the mean log-transformed produced duration ( $r = .364$ ,  $p < .01$ ), and that the relationship is even stronger among females ( $r = .500$ ,  $p < .005$ ).

#### 4. Discussion

We present here a mixed bag of results, all of which to our mind will encourage further attention, both in our own work, and hopefully in that of others. We have shown that PAF is, indeed, related to time production—once we uncovered the fact that we had a suppression situation in our data set. Given the accepted view, that studies attempting to link between EEG alpha and the internal clock are dead-ends (Block, 1990), we can now certainly revive research interest in this arena. We have further shown that this relationship is even stronger among females. Our pattern of results suggests that following motor activity, there is a sharp decrease in PAF during time production, but not during baseline for females. Furthermore, for them there is a global post-pre decrease in alpha power, coupled with an anterior-posterior hemispheric torque: Frontal post-pre left alpha power > frontal post-pre right alpha power; parietal post-pre left alpha power < parietal post-pre right alpha power. Following relaxed wakefulness, there is a global post-pre increase in alpha power, the data for the females showing more differentiation of task from baseline, relative to those of the males.

Given that these are control conditions for two studies currently in progress, we will be able to shed more light here on these differential trends in the future. Yet, some reservations should be expressed at the outset.

The first that comes to mind is concerned with the issue of chronometric counting. Our instructions did not actively discourage this (Brown, Newcomb, & Kahrl, 1995; Fetterman & Killeen, 1990), and given the range of durations employed (Coelho *et al.*, 2004), we are not at all surprised by the fact that all of our participants were engaged in counting during the task. We therefore stress the fact that participants employing chronometric counting might well be instantiating an internal clock, in the sense that "the movement of the vocal apparatus, with its resonant frequency around 4 Hz, constitutes the pacemaker; the number system constitutes the register; the initiation of counting in response to the interval onset constitutes gating; the matching of the counts registered with a target constitutes the comparison" (Bizo, Chu, Sanabria, & Killeen, 2006, p. 201). Counting, implicit or explicit, seems to be a key factor underlying the thoughts of a number of fellow researchers (Wackerman, 2007, p. 29; Wearden, 1991, p. 71; Zakay 1993, p. 662). Whether the relationship between PAF and time production is dependent on chronometric counting or not, is a question that requires immediate research attention.

The second reservation concerns the issue of sex or gender differences in time perception. As opposed to some previous work using the same task (Glicksohn 2004), we did not uncover differences between males and females in time production. This is even more surprising, given the role that such differences play in our electrophysiological indices. One would expect for females to make shorter time productions than males (Block, Hancock, & Zakay, 2000; Carlson & Feinberg, 1970), and yet in the present study the data at test for females ( $n = 30$ ;  $M = 3.63$ ) and for males ( $n = 21$ ;  $M = 3.64$ ) are not supportive. We shall continue to explore this issue in subsequent work.

The third reservation refers to the topography of alpha (and theta) reported here. While some authors might be perturbed about the elevated incidence of alpha frontally

(Niedermeyer, 2003), it is also clear that others would well expect this (Laufs *et al.*, 2003). We have noted the dip in alpha power, centrally, though we have seen such a trend in the data of others (Desarkar, Sinha, Jagadheesan, & Nizamie, 2007; Gamma *et al.*, 2000). We further note that given the notion of an anterior-posterior hemispheric torque in alpha power, the flip-flop in asymmetry should implicate a point of inflexion, centrally. How and whether

this pattern of results is related to motor activity or relaxed wakefulness is an issue that should be further explored.

#### 5. Acknowledgments

We thank Simon Grondin and an anonymous reviewer for their helpful comments on an earlier draft. Correspondence should be addressed to Joseph Glicksohn, Department of Criminology, and The Leslie and Susan Gonda (Goldschmied) Multidisciplinary Brain Research Center, Bar-Ilan University, Ramat Gan, 52100, Israel.

#### References

- Adam N, Rosner BS, Hosick EC, Clark DL. Effect of anesthetic drugs on time production and alpha rhythm. *Perception & Psychophysics* 1971;10(3):133-136.
- Allan LG. The perception of time. *Perception & Psychophysics* 1979;26(5):340-354.
- Allan LG. Magnitude estimation of temporal intervals. *Perception & Psychophysics* 1983;33(1):29-42.
- Allan LG. The influence of the scalar timing model on human timing research. *Behavioural Processes* 1998;44(2):101-117.
- Anderson KJ. Arousal and the inverted-U hypothesis: A critique of Neiss's "Reconceptualizing arousal". *Psychological Bulletin* 1990;107(1):96-100.
- Angelakis E, Lubar JF, Stathopoulou S. Electroencephalographic peak alpha frequency correlates of cognitive traits. *Neuroscience Letters* 2004;371(1):60-63.
- Angelakis E, Lubar JF, Stathopoulou S, Kounios J. Peak alpha frequency: An electroencephalographic measure of cognitive preparedness. *Clinical Neurophysiology* 2004;115(4):887-897.
- Arzouan Y, Goldstein A, Faust M. Dynamics of hemispheric activity during metaphor comprehension: Electrophysiological measures. *NeuroImage* 2007;36(1):222-231.
- Barlow JS. *The electroencephalogram: Its patterns and origins*. Cambridge, MA: MIT Press; 1993.
- Basso G, Nichelli P, Wharton CM, Peterson M, Grafman J. Distributed neural systems for temporal production: A functional MRI study. *Brain Research Bulletin* 2003;59(5):405-411.
- Baudouin A, Vanneste S, Isingrini M, Pouthas V. Differential involvement of internal clock and working memory in the production and reproduction of duration: A study on older adults. *Acta Psychologica* 2006;121(3):285-296.
- Bindra D, Waksberg H. Methods and terminology in studies of time estimation. *Psychological Bulletin* 1956;53:155-159.
- Binkofski F, Block RA. Accelerated time experience after left frontal cortex lesion. *Neurocase* 1996;2(6):485-493.
- Bizo LA, Chu JYM, Sanabria F, Killeen PR. The failure of Weber's law in time perception and production. *Behavioural Processes* 2006;71(2-3):201-210.
- Block RA. Models of psychological time. In: Block RA, editor. *Cognitive models of psychological time*. Hillsdale, NJ: Lawrence Erlbaum Associates, Inc; 1990. p. 1-35.
- Block RA, Hancock PA, Zakay D. Sex differences in duration judgments: A meta-analytic review. *Memory & Cognition* 2000;28(8):1333-1346.
- Borg GAV, Marks LE. Twelve meanings of the measure constant in psychophysical power functions. *Bulletin of the Psychonomic Society* 1983;21(1):73-75.
- Brown SW, Newcomb DC, Kahrl KG. Temporal-signal detection and individual differences in timing. *Perception* 1995;24(5):525-538.
- Brown SW, Stubbs DA. The psychophysics of retrospective and prospective timing. *Perception* 1988;17(3):297-310.
- Brown SW, Stubbs DA. Attention and interference in prospective and retrospective timing. *Perception* 1992;21(4):545-557.
- Burle B, Casini L. Dissociation between activation and attention effects in time estimation: Implications for internal clock models. *Journal of Experimental Psychology: Human Perception and Performance* 2001;27(1):195-205.
- Cahn BR, Polich J. Meditation states and traits: EEG, ERP, and neuroimaging studies. *Psychological Bulletin* 2006;132(2):180-211.
- Cahoon RL. Physiological arousal and time estimation. *Perceptual and Motor Skills* 1969;28(1):259-268.
- Carlson VR, Feinberg I. Individual variations in time judgment and the concept of an internal clock. *Journal of Experimental Psychology* 1968;77(4):631-640.
- Carlson VR, Feinberg I. Time judgment as a function of method, practice, and sex. *Journal of Experimental Psychology* 1970;85(2):171-180.
- Clark CR, Veltmeyer MD, Hamilton RJ, Simms E, Paul R, Hermens D, et al. Spontaneous alpha peak frequency predicts working memory performance across the age span. *International Journal of Psychophysiology* 2004;53(1):1-9.
- Coelho M, Ferreira JJ, Dias B, Sampaio C, Martins IP, Castro-Caldas A. Assessment of time perception: The effect of aging. *Journal of the International Neuropsychological Society* 2004;10(3):332-341.

- Coffin S, Ganz L. Perceptual correlates of variability in duration of the cortical excitability cycle. *Neuropsychologia* 1977;15(2):231-241.
- Desarkar P, Sinha VK, Jagadheesan K, Nizamie SH. A high resolution quantitative EEG power analysis of obsessive-compulsive disorder. *German Journal of Psychiatry* 2007;10(2):29-35.
- Eisler H. Experiments on subjective duration 1868-1975: A collection of power function exponents. *Psychological Bulletin* 1976;83(6):1154-1171.
- Fahrenberg J. Psychophysiological processes. In: Nesselroade JR, Cattell RB, editors. *Handbook of multivariate experimental psychology*. second ed. New York: Plenum; 1988. p. 867-914.
- Ferree TC, Luu P, Russell GS, Tucker DM. Scalp electrode impedance, infection risk, and EEG data quality. *Clinical Neurophysiology* 2001;112(3):536-544.
- Fetterman JG, Killeen PR. A componential analysis of pacemaker-counter timing systems. *Journal of Experimental Psychology: Human Perception and Performance* 1990;16(4):766-780.
- Fraisse P. Perception and estimation of time. *Annual Review of Psychology* 1984;35:1-36.
- Gamma A, Frei E, Lehmann D, Pascual-Marqui RD, Hell D, Vollenweider FX. Mood state and brain electric activity in Ecstasy users. *NeuroReport* 2000;11(1):157-162.
- Gibbons H, Rammsayer TH. Current-source density analysis of slow brain potentials during time estimation. *Psychophysiology* 2004;41(6):861-874.
- Glicksohn J. Entering trait and context into a cognitive-timer model for time estimation. *Journal of Environmental Psychology* 1996;16(4):361-370.
- Glicksohn J. Temporal cognition and the phenomenology of time: A multiplicative function for apparent duration. *Consciousness and Cognition* 2001;10(1):1-25.
- Glicksohn J. Disentangling the components of a multiplicative function for apparent duration. In: Berglund B, Borg E, editors. *Fechner Day 2003: Proceedings of the Nineteenth Annual Meeting of the International Society for Psychophysics*. Stockholm: International Society for Psychophysics; 2003. p. 109-114.
- Glicksohn J. Sex differences in prospective timing: Can one pinpoint the effect? In: Oliveira AM, Teixeira M, Borges GF, Ferro MJ, editors. *Fechner Day 2004: Proceedings of the Twentieth Annual Meeting of the International Society for Psychophysics*. Coimbra: International Society for Psychophysics; 2004. p. 152-157.
- Grieve PG, Emerson RG, Fifer WP, Isler JR, Stark RI. Spatial correlation of the infant and adult electroencephalogram. *Clinical Neurophysiology* 2003;114(9):1594-1608.
- Grondin S. From physical time to the first and second moments of psychological time. *Psychological Bulletin* 2001;127(1):22-44.
- Grondin S, Meilleur-Wells G, Lachance R. When to start explicit counting in a time-intervals discrimination task: A critical point in the timing process of humans. *Journal of Experimental Psychology: Human Perception and Performance* 1999;25(4):993-1004.
- Grondin S, Ouellet B, Roussel M-E. Benefits and limits of explicit counting for discriminating temporal intervals. *Canadian Journal of Experimental Psychology* 2004;58(1):1-12.
- Hagemann D. Individual differences in anterior EEG asymmetry: Methodological problems and solutions. *Biological Psychology* 2004;67(1-2):157-182.
- Hillman CH, Erickson KI, Kramer AF. Be smart, exercise your heart: exercise effects on brain and cognition. *Nature Reviews Neuroscience* 2008;9(1):58-65.
- Hinton SC, Harrington DL, Binder JR, Durgerian S, Rao SM. Neural systems supporting timing and chronometric counting: An fMRI study. *Cognitive Brain Research* 2004;21(2):183-192.
- Hinton SC, Rao SM. "One-thousand *one...* one-thousand *two...* ": Chronometric counting violates the scalar property in interval timing. *Psychonomic Bulletin & Review* 2004;11(1):24-30.
- Ivry RB, Hazeltine RE. Models of timing-with-a-timer. In: Macar F, Pouthas V, Friedman WJ, editors. *Time, action and cognition: Towards bridging the gap*. Dordrecht: Kluwer Academic Publishers; 1992. p. 183-189.
- Ivry RB, Hazeltine RE. Perception and production of temporal intervals across a range of durations: Evidence for a common timing mechanism. *Journal of Experimental Psychology: Human Perception and Performance* 1995;21(1):3-18.
- Jacobs GD, Friedman R. EEG spectral analysis of relaxation techniques. *Applied Psychophysiology and Biofeedback* 2004;29(4):245-254.
- Jin Y, O'Halloran JP, Plon L, Sandman CA, Potkin SG. Alpha EEG predicts visual reaction time. *International Journal of Neuroscience* 2006;116(9):1035-1044.
- Killeen PR. Counting the minutes. In: Macar F, Pouthas V, Friedman WJ, editors. *Time, action and cognition: Towards bridging the gap*. Dordrecht: Kluwer Academic Publishers; 1992. p. 203-214.
- Kladopoulos CN, Hemmes NS, Brown BL. Prospective timing under dual-task paradigms: Attentional and contextual-change mechanisms. *Behavioural Processes* 2004;67(2):221-233.
- Klimesch W, Sauseng P, Gerloff C. Enhancing cognitive performance with repetitive transcranial magnetic stimulation at human individual alpha frequency. *European Journal of Neuroscience* 2003;17(5):1129-1133.
- Kounios J, Fleck JI, Green DL, Payne L, Stevenson JL, Bowden EM, et al. The origins of insight in resting-state brain activity. *Neuropsychologia* 2008;46(1):281-291.
- Lalonde R, Hannequin D. The neurobiological basis of time estimation and temporal order. *Reviews in the Neurosciences* 1999;10(2):151-173.
- Laufs H, Kleinschmidt A, Beyerle A, Eger E, Salek-Haddadi A, Preibisch C, et al. EEG-correlated fMRI of human alpha activity. *NeuroImage* 2003;19(4):1463-1476.
- Legg CF. Alpha rhythm and time judgments. *Journal of Experimental Psychology* 1968;78(1):46-49.
- Lewis PA. Finding the timer. *Trends in Cognitive Sciences* 2002;6(5):195-196.
- Lewis PA, Miall RC. Remembering the time: A continuous clock. *Trends in Cognitive Sciences* 2006;10(9):401-406.
- Macar F. Time psychophysics and related models. In: Michon JA, Jackson JL, editors. *Time, mind, and behavior*. New York: Springer-Verlag; 1985. p. 112-130.
- Macar F. Central and peripheral mechanisms in timing. In: Fraser JT, Rowell L, editors. *Time and process: Interdisciplinary issues (The study of time VII)*.

- Madison, CT: International Universities Press; 1993. p. 109-124.
- Macar F, Vidal F. Timing processes: An outline of behavioural and neural indices not systematically considered in timing models. *Canadian Journal of Experimental Psychology* in press.
- Makhin SA, Pavlenko VB. EEG activity in the process of measuring-off of time intervals by humans. *Neurophysiology* 2003;35(2):143-148.
- Mantini D, Perrucci MG, Del Gratta C, Romani GL, Corbetta M. Electrophysiological signatures of resting state networks in the human brain. *Proceedings of the National Academy of Sciences of the United States of America* 2007;104(32):13170-13175.
- Marchetti G. Studies on time: a proposal on how to get out of circularity. *Cognitive Processing* 2008:1-34.
- Mazoyer B, Zago L, Mellet E, Bricogne S, Etard O, Houdé O, et al. Cortical networks for working memory and executive functions sustain the conscious resting state in man. *Brain Research Bulletin* 2001;54(3):287-298.
- McDonald J, Schleifer L, Richards JB, de Wit H. Effects of THC on behavioral measures of impulsivity in humans. *Neuropsychopharmacology* 2003;28(7):1356-1365.
- Mimura M, Kinsbourne M, O'Connor M. Time estimation by patients with frontal lesions and by Korsakoff amnesics. *Journal of the International Neuropsychological Society* 2000;6(5):517-528.
- Miró E, Cano MC, Espinosa-Fernández L, Buela-Casal G. Time estimation during prolonged sleep deprivation and its relation to activation measures. *Human Factors* 2003;45(1):148-159.
- Mohl W, Pfurtscheller G. The role of the right parietal region in a movement time estimation task. *NeuroReport* 1991;2(6):309-312.
- Myers PM, Tilley A. The relationship between diurnal type and time duration estimation at morning and evening times of day. *Personality and Individual Differences* 2003;35(5):1141-1150.
- N'Diaye K, Ragot R, Garnero L, Pouthas V. What is common to brain activity evoked by the perception of visual and auditory filled durations? A study with MEG and EEG co-recordings. *Cognitive Brain Research* 2004;21(2):250-268.
- Neuper C, Grabner RH, Fink A, Neubauer AC. Long-term stability and consistency of EEG event-related (de-)synchronization across different cognitive tasks. *Clinical Neurophysiology* 2005;116(7):1681-1694.
- Niedermeyer E. Electrophysiology of the frontal lobe. *Clinical Electroencephalography* 2003;34(1):5-12.
- Noulhiane M, Mella N, Samson S, Ragot R, Pouthas V. How emotional auditory stimuli modulate time perception. *Emotion* 2007;7(4):697-704.
- Nunez PL, Srinivasan R, Westdorp AF, Wijesinghe RS, Tucker DM, Silberstein RB, et al. EEG coherence 1: Statistics, reference electrode, volume conduction, Laplacians, cortical imaging, and interpretation at multiple scales. *Electroencephalography and Clinical Neurophysiology* 1997;103(5):499-515.
- Oken BS, Chiappa KH. Short-term variability in EEG frequency analysis. *Electroencephalography and Clinical Neurophysiology* 1988;69(3):191-198.
- Osaka M. Peak alpha frequency of EEG during a mental task: Task difficulty and hemispheric differences. *Psychophysiology* 1984;21(1):101-105.
- Osaka M, Osaka N, Koyama S, Okusa T, Kakigi R. Individual differences in working memory and the peak alpha frequency shift on magnetoencephalography. *Cognitive Brain Research* 1999;8(3):365-368.
- Ozel S, Larue J, Dosseville F. Effect of arousal on internal clock speed in real action and mental imagery. *Canadian Journal of Experimental Psychology* 2004;58(3):196-205.
- Pouthas V, Perbal S. Time perception depends on accurate clock mechanisms as well as unimpaired attention and memory processes. *Acta Neurobiologiae Experimentalis* 2004;64(3):367-385.
- Rubia K, Smith A. The neural correlates of cognitive time management: A review. *Acta Neurobiologiae Experimentalis* 2004;64(3):329-340.
- Rubia K. The neural correlates of timing functions. In: Glicksohn J, Myslobodsky MS, editors. *Timing the future: The case for a time-based prospective memory*. London: World Scientific; 2006. p. 213-238.
- Rule SJ. Analyzing coefficients of psychophysical power functions. *Perception & Psychophysics* 1993;54(4):439-445.
- Rule SJ, Curtis DW. Ordinal properties of perceived average duration: Simultaneous and sequential presentations. *Journal of Experimental Psychology: Human Perception and Performance* 1985;11(4):509-516.
- Ryan LJ, Henry K, Robey T, Edwards JA. Resolution of conflicts between internal and external information sources on a time reproduction task: The role of perceived information reliability and attributional style. *Acta Psychologica* 2004;117(2):205-229.
- Salinsky MC, Oken BS, Morehead L. Test-retest reliability in EEG frequency analysis. *Electroencephalography and Clinical Neurophysiology* 1991;79(5):382-392.
- Smith A, Taylor E, Lidzba K, Rubia K. A right hemispheric frontocerebellar network for time discrimination of several hundreds of milliseconds. *NeuroImage* 2003;20(1):344-350.
- Tracy JL, Faro SH, Mohamed FB, Pinsk M, Pinus A. Functional localization of a "time keeper" function separate from attentional resources and task strategy. *NeuroImage* 2000;11(3):228-242.
- Treisman M. Temporal discrimination and the indifference interval: Implications for a model of the "internal clock". *Psychological Monographs: General and Applied* 1963;77(13):Whole No. 576.
- Treisman M. Temporal rhythms and cerebral rhythms. In: Gibbon J, Allan L, editors. *Timing and time perception (Annals of the New York Academy of Sciences)*. New York; 1984. p. 542-565.
- Treisman M, Brogan D. Time perception and the internal clock: Effects of visual flicker on the temporal oscillator. *European Journal of Cognitive Psychology* 1992;4(1):41-70.
- Treisman M, Cook N, Naish PLN, MacCrone JK. The internal clock: Electroencephalographic evidence for oscillatory processes underlying time perception. *The Quarterly Journal of Experimental Psychology* 1994;47A(2):241-289.
- Treisman M, Faulkner A, Naish PLN, Brogan D. The internal clock: Evidence for a temporal oscillator underlying time perception with some estimates of its characteristic frequency. *Perception* 1990;19(6):705-743.

- Tzelgov J, Henik A. Suppression situations in psychological research: Definitions, implications, and applications. *Psychological Bulletin* 1991;109(3):524-536.
- Wackermann J. Inner and outer horizons of time experience. *The Spanish Journal of Psychology* 2007;10(1):20-32.
- Wearden JH. Do humans possess an internal clock with scalar timing properties? *Learning and Motivation* 1991;22(1-2):59-83.
- Wearden JH, Culpin V. Exploring scalar timing theory with human subjects. In: De Keyser V, d'Ydewalle G, Vandierendonck A, editors. *Time and the dynamic control of behavior*. Seattle: Hogrefe & Huber; 1998. p. 33-49.
- Wearden JH, Denovan L, Fakhri M, Haworth R. Scalar timing in temporal generalization in humans with longer stimulus durations. *Journal of Experimental Psychology: Animal Behavior Processes* 1997;23(4):502-511.
- Wearden JH, Philpott K, Win T. Speeding up and (... relatively ...) slowing down an internal clock in humans. *Behavioural Processes* 1999;46(1):63-73.
- Zakay D. The evasive art of subjective time measurement: Some methodological dilemmas. In: Block RA, editor. *Cognitive models of psychological time*. Hillsdale, NJ: Lawrence Erlbaum Associates, Inc; 1990. p. 59-84.
- Zakay D. Relative and absolute duration judgments under prospective and retrospective paradigms. *Perception & Psychophysics* 1993;54(5):656-664.
- Zakay D, Block RA. Temporal cognition. *Current Directions in Psychological Science* 1997;6(1):12-16.
- Zakay D, Block RA, Tsal Y. Prospective duration estimation and performance. In: Gopher D, Koriat A, editors. *Attention and performance XVII. Cognitive regulation of performance: Interaction of theory and application*. Cambridge, MA: MIT Press; 1999. p. 557-580.